Development of Shaped Boom Filters for Estimating Atmospheric Turbulence Effects on X-59 Sonic Thumps

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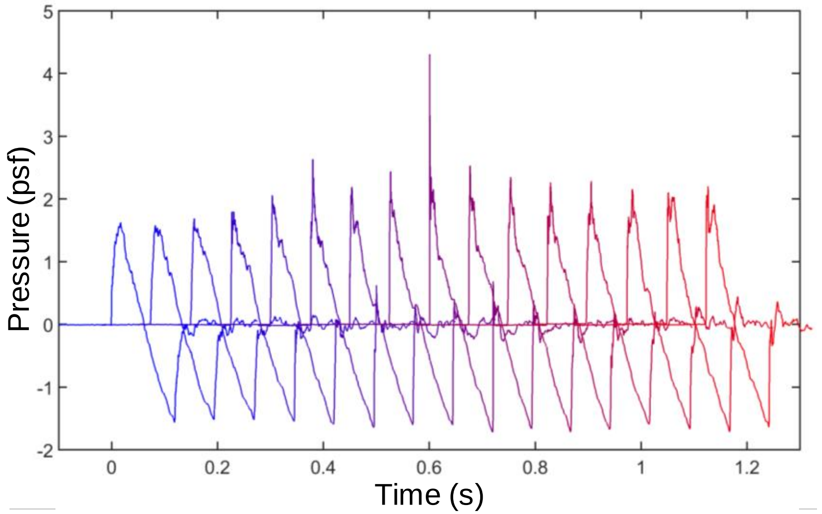
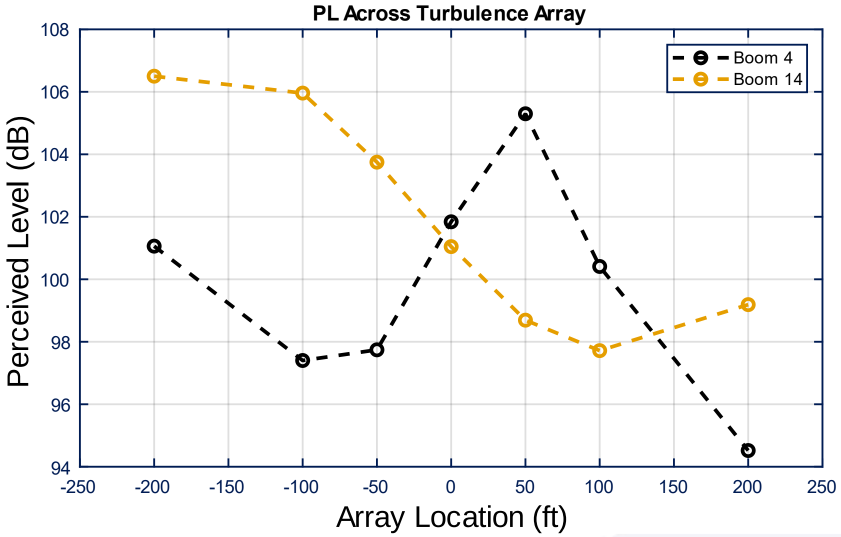
Background on measured atmospheric turbulence effects

- **Variation in measured ground waveforms observed during 2016 NASA SonicBAT measurements**
  - F-18 in steady flight
  - 16-mic linear undertrack array with 100-ft spacing
- **Similar variation observed in 2019 NASA CarpetDIEM I measurements**
  - F-18 in steady flight
  - 7-mic 400-ft array
- **Atmospheric turbulence introduces large variations in ground waveforms and metric levels**
- **This poses challenges for accurately estimating dose during X-59 community testing**



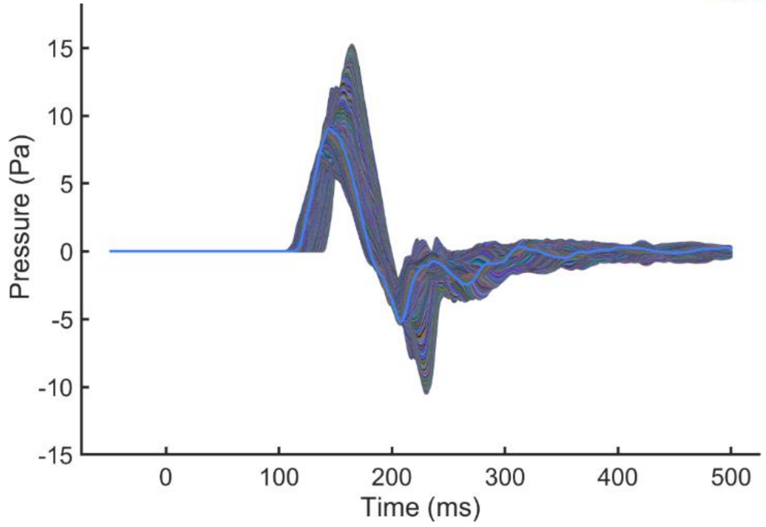
Bradley et al., NASA/CR–2020–220509 (2020)

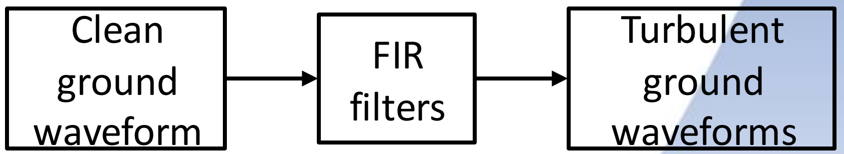


Durrant et al., POMA, Vol. 43, 045002 (2022)

Limitations in modeling atmospheric turbulence effects

- **Simulation tools such as KZKFourier (Stout and Sparrow) can be used to model turbulence effects, but are computationally expensive**
  - Plotted simulation results required wall time of approx. 46 hours
- **FIR filters that quickly estimate atmospheric turbulence effects in Atmospheric Boundary Layer (ABL) were developed for N-waves (Locey and Sparrow, Stout and Sparrow)**
  - Currently available in PCBoom v7.3
  - Issues observed with applying filters to shaped booms
  - Developed for turbulence parameter ranges corresponding only to SonicBAT tests (two US locations)
- **Need for a quick estimation method that is relevant for X-59 signatures**

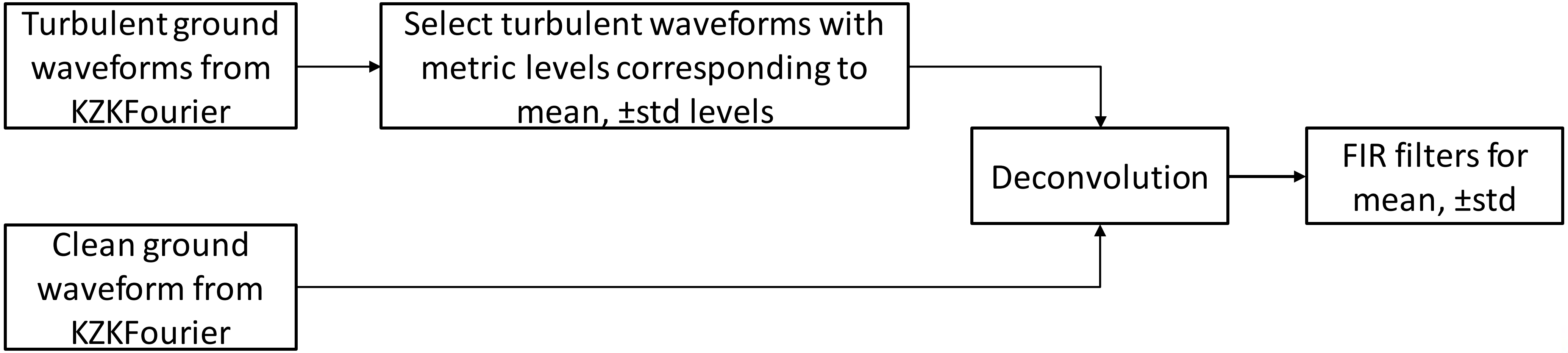




Locey and Sparrow, "Modeling Atmospheric Turbulence as a Filter for Sonic Boom Propagation," NCEJ 55, 2007.
Stout and Sparrow, "Atmospheric turbulence effects on shaped and unshaped sonic boom signatures," JASA 151 (5), 2022.

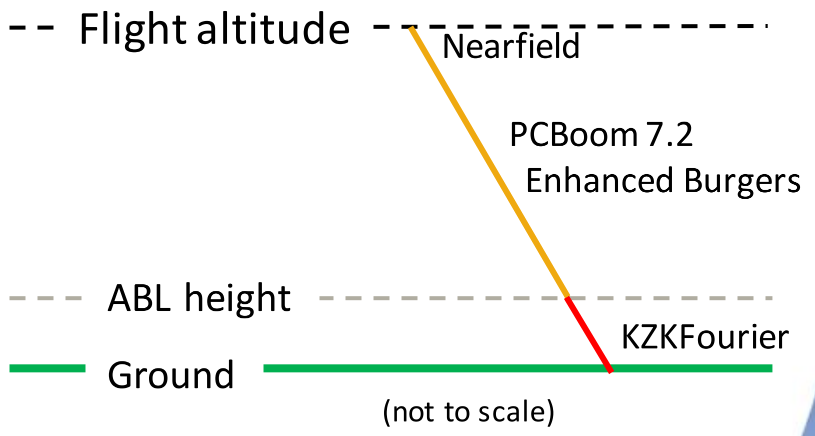
New shaped boom filters developed using simulations

- KZKFourier run with X-59 shaped boom input
- Variety of atmospheric conditions spanning expected range across U.S.
- FIR filters developed corresponding to metric mean and mean ± std
- Filters can then be applied to new clean waveforms to quickly estimate turbulence effects



KZKFourier simulation code run with X-59 input

- **Propagation model for ABL is the KZK equation**
  - Models diffraction effects, thermoviscous absorption, molecular relaxation, nonlinearity, and includes temperature and velocity fluctuations
  - Turbulence modeled as fields of velocity and temperature fluctuations
  - Turbulence fields are frozen



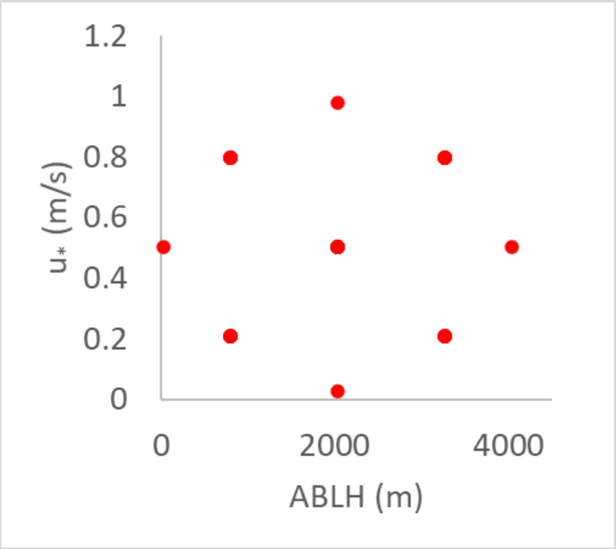
- **Run multiple cases, each with multiple realizations**
- **Input waveform conditions**
  - Near-field pressure: X-59 C612A on design (FUN3D 20210929)
  - Trajectory: steady, level flight at Mach 1.4, altitude 52,026 ft
  - Atmosphere: Revised Reference Day from ICAO
    - Temperature and pressure profiles from ICAO 7488/3
    - RH profiles from ISO 5878 Add. 2 – 50 deg N annual median up to 8 km, ISO 9613-1 Annex C above 8 km
    - No wind

Simulation matrix design covers range of conditions

- **Design of Experiments approach: Central Composite Design**
  - Minimize computation time to cover high-dimension parameter space
- **Parameter space comprises 5 levels of 7 design factors**

Parameter	Values
Turbulence strength	$u_* = 0.03, 0.21, 0.50, 0.80, 0.98$ $w_* = 0.10, 0.82, 1.96, 3.11, 3.83$ $T_* = 0.21, -0.21, -0.87, -1.54, -1.96$
ABL height	24, 797, 2030, 3262, 4035 m
Relative humidity	5, 23, 52, 82, 100%
Surface pressure	0.83, 0.87, 0.93, 0.98, 1.02 atm
Surface temp	256, 269, 291, 313, 327 K

Example of two parameters

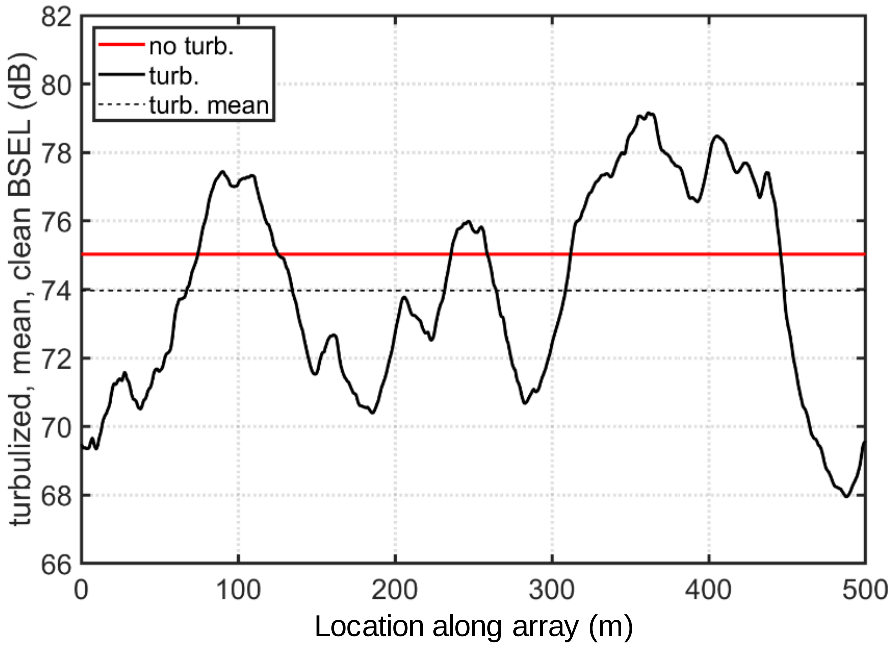


- **Ranges of parameters**
  - Ranges of each factor based on 10-year meteorological datasets for 19 airfields across U.S.

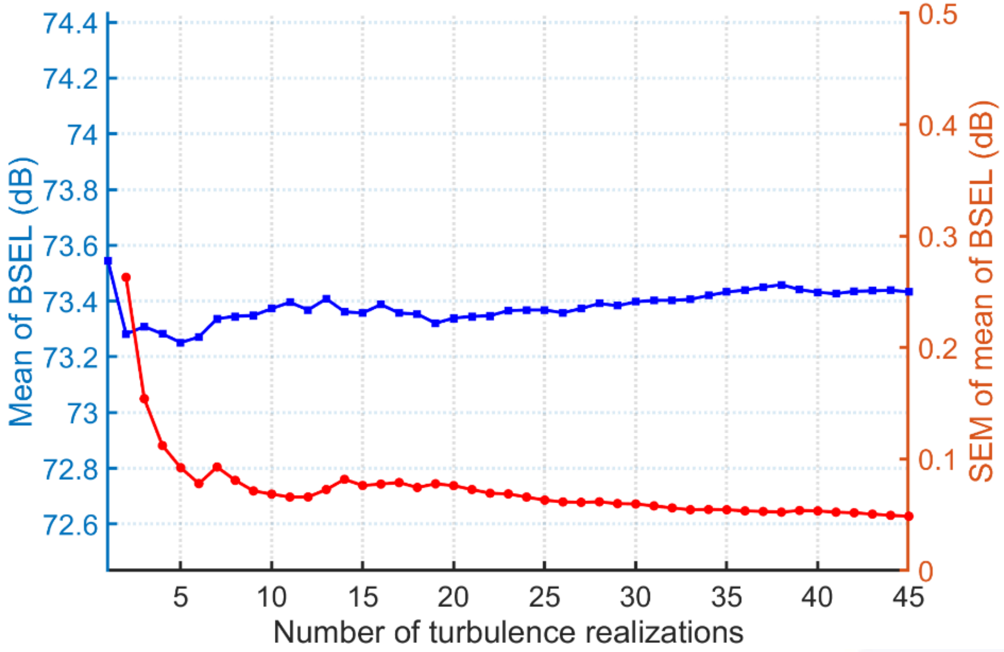
KZKFourier results converge with 30 realizations

- **45 cases x 30 turbulence realizations x 1000 – 2000 ground waveforms**
  - Used combination of NASA K cluster high performance computing resource and Volpe systems
  - Each turbulence realization (45 cases) ~ 1,128 hours
  - Evaluated convergence with increasing realizations
  - With 30 realizations, 95% CI < 0.22 dB for all metrics

Example ground metrics for one realization

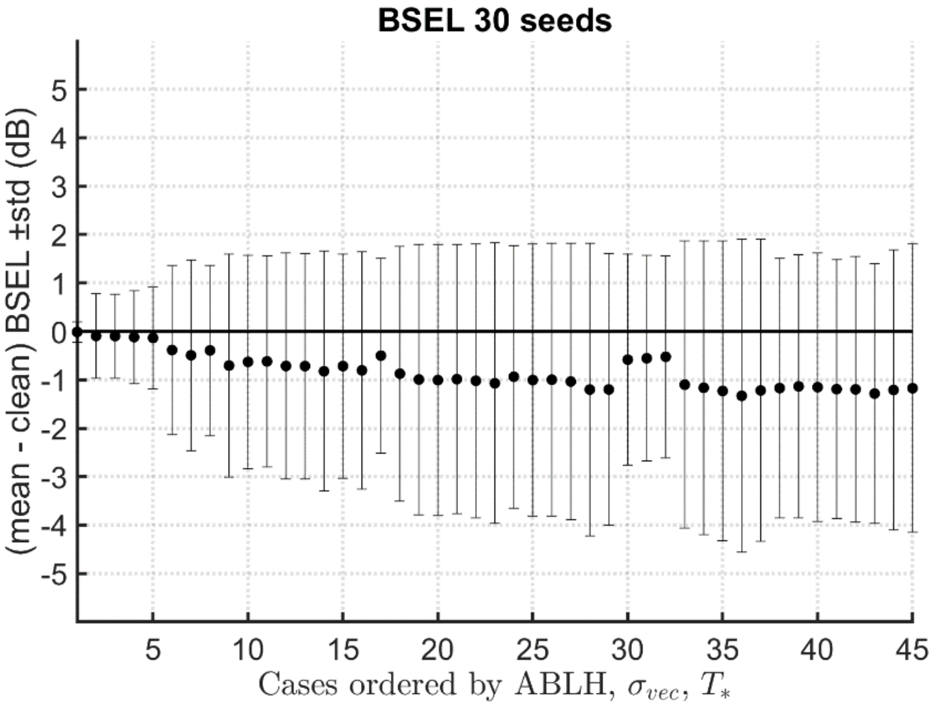


Example convergence for one case



KZKFourier results indicate most important factors

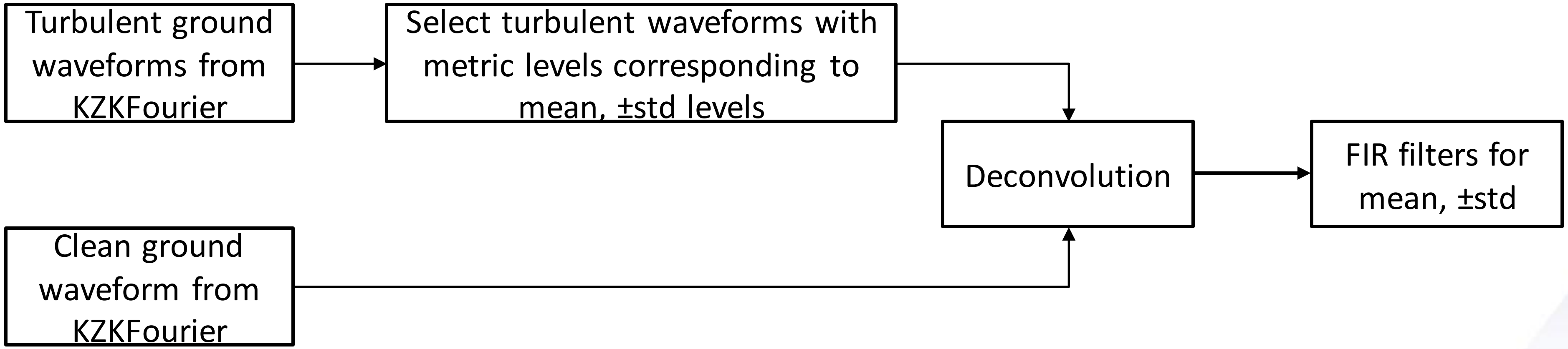
- **For all cases considered, mean metric levels < no-turbulence metric levels**



- **Empirical model analysis to identify relative sensitivity of metrics to simulation factors. Most significant factors:**
  - ABL height
  - σ_{vec} $(= \sqrt{3.0u_*^2 + 0.35w_*^2})$
  - (ABL height)^2
  - Surface temperature
- **Increasing ABL height or σ_{vec} generally reduces mean metric**

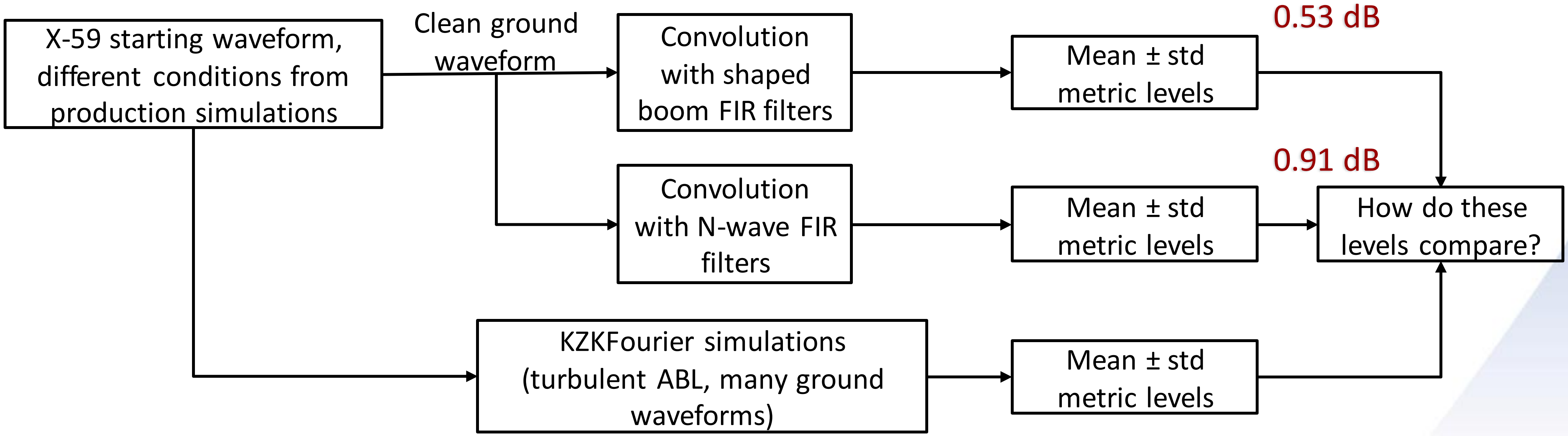
Shaped boom FIR filters developed for faster run times

- **Use KZKFourier production simulations to generate FIR filters**
  - Metrics PL, ASEL, BSEL, DSEL, ESEL, ISBAP
  - 45 design points $\times$ 6 metrics $\times$ 3 statistics (mean-std, mean, mean+std) = 810 filters
- **Follow procedure developed by Stout and Sparrow**
  - For each metric and statistic, select all waveforms with levels $\pm$0.005 dB of target level → approx. 50 waveforms on average
  - Select waveform with median rise location in time domain (median advection)
  - Signal processing of waveforms input to matrix deconvolution process and FIR filter coefficient outputs
    - Settings adjusted for X-59 signals



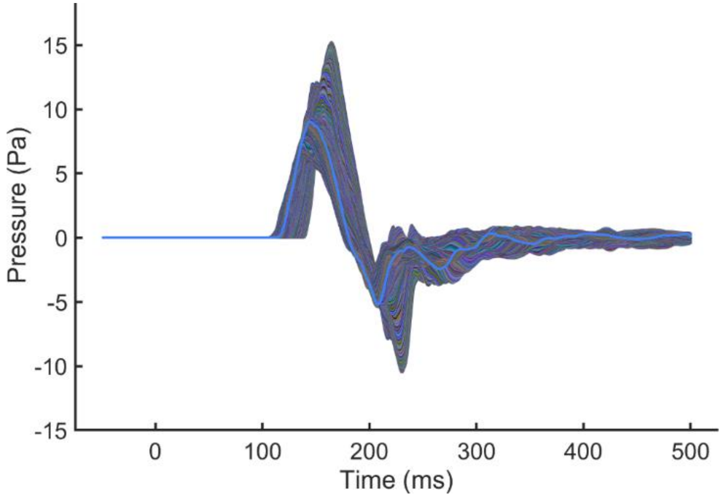
Verification testing of FIR filters vs. KZKFourier baseline

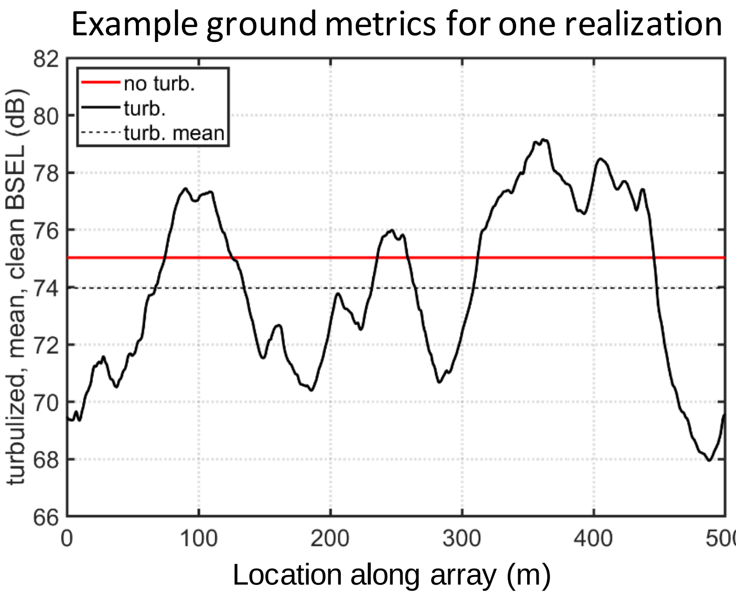
- **Circular check quantifies how well FIR filtered waveform metrics match KZKFourier results for same test case**
  - Overall mean absolute error of 0.1 dB
- **Verification testing uses different near field pressures, ambient atmospheric conditions, and turbulence conditions**
  - 19 verification test cases give overall error of 0.53 dB (error reduces to 0.39 dB for on-design cases)

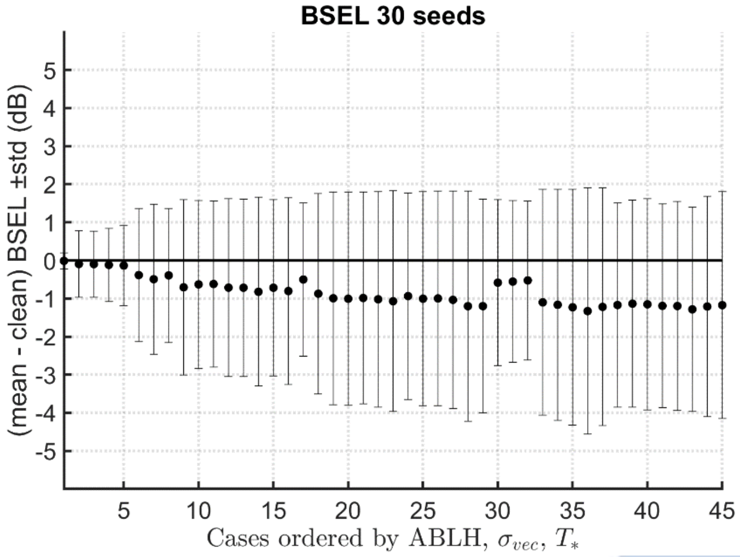


Summary of shaped boom filter development

- **KZKFourier simulations of shaped boom waveforms used to generate a new bank of 810 FIR filters for estimating turbulence effects (included in next PCBoom release)**
  - PL, ASEL, BSEL, DSEL, ESEL, and ISBAP metrics
  - For each metric: mean−std, mean, and mean+std
- **Filter accuracy was benchmarked against KZKFourier and compared with PCBoom N-wave turbulence filters developed as part of SonicBAT**
  - Results from application of new shaped boom filter have an overall mean absolute error lower than SonicBAT N-wave filters (0.91 dB → 0.53 dB)
  - On-design configurations 0.96 dB → 0.39 dB (15 cases)
  - Max-loudness configuration 0.72 dB → 1.02 dB (4 cases)
- **Future work addresses limitations in FIR filter method**
- **Upcoming dissemination:**
  - Three presentations at May 2023 ASA meeting in Chicago
  - Technical document drafted encompassing KZKFourier simulations, filter development, and testing, to be released as a NASA TM







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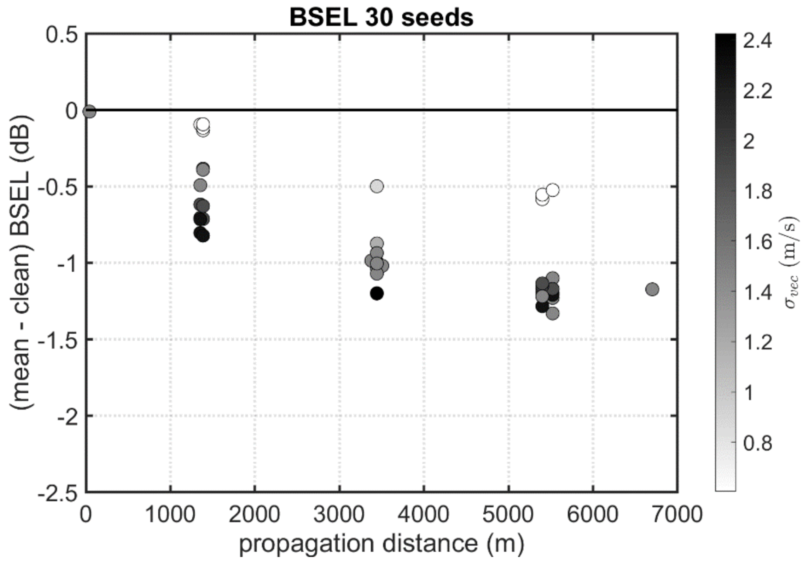
Backup Slides

KZKFourier results with propagation distance

- Metric means and standard deviations generally correlate with propagation distance: longer propagation -> larger reduction in mean level compared with no-turbulence level



Future work addresses limitations in FIR filter method

- **Refinement of how filters are selected**
  - Filter lookup based on inverse distance weighting among parameters
  - Could be adjusted taking into account significance of factors
- **Enhanced filtering approach**
  - Use ensemble of FIR filters to form metric statistics
  - Pack filters into binary files to reduce storage space
  - Preliminary investigation shows a decrease in overall error, even for max loudness case